

# Testing Lorentz symmetry with atoms and light

Neil Russell

Physics Department, Northern Michigan University, Marquette, MI, USA

E-mail: nrussell@nmu.edu

**Abstract.** This article reports on the Fifth Meeting on CPT and Lorentz Symmetry, CPT '10, held at the end of June 2010 in Bloomington, Indiana, USA. The focus is on recent tests of Lorentz symmetry using atomic and optical physics.

## 1. Introduction

Experiments with atoms, molecules, and electromagnetic waves have a remarkable track record of innovations and sensitivity improvements. As the technology has advanced, new views of the details of nature have become possible. Recently, atom interferometers have probed the gravitational redshift [1], comagnetometers have sought spin couplings at unprecedented levels [2], antihydrogen has been cornered in an electromagnetic trap [3], and rotating optical resonators have sought delicate anisotropies in the speed of light [4, 5].

These experiments have created new opportunities for exploring the fundamental symmetries of nature. One area is Lorentz symmetry, the hypothesis that experiments give the same results regardless of their inertial reference frame and regardless of their orientation. Closely related is the hypothesis of CPT symmetry, that the outcome of an experiment must be the same as that of its CPT image [6]. This image is constructed by replacing each charge with its conjugate, by parity-reversing the entire physical configuration, and by reversing all initial velocities so that time runs ‘backwards.’ These two fundamental symmetries have withstood hundreds of tests spanning decades, although recently anomalous effects with mesons and neutrinos have provided hints of possible symmetry breaking [7, 8].

The discovery of Lorentz and CPT symmetry breaking would necessitate fundamental changes in the conventional theories of gravity and quantum mechanics. It would cause a stir in the community, since the nature of the violation would most likely hold essential information about a realistic quantum-gravity theory. Since violations of these symmetries have never been seen, they are likely to be minuscule or

countershaded by weak-gravity couplings. One challenge of detecting them is attaining sufficient experimental sensitivity to signals. Another is designing experiments with sensitivity to likely types of unconventional signal, and this implies the need for a theoretical framework that incorporates Lorentz and CPT violations. The Standard-Model Extension (SME), developed over a period of more than 20 years, and first published in basic form in the mid 1990s, does just this, providing a detailed theoretical framework containing all possible Lorentz and CPT breaking terms at the level of the fundamental particles and interactions [9]. The deep interest in exploring Lorentz and CPT symmetry can be attributed to the confluence of these circumstances – strong theoretical motivations, advancing experimental techniques, and the multitudes of measurable coefficients for Lorentz and CPT violation. This interest was clearly evident at the *Fifth Meeting on Lorentz and CPT Symmetry*, CPT '10, held in Bloomington, Indiana, at the end of June 2010.

This conference report summarizes the content of the CPT '10 meeting, focusing in particular on AMO physics. Since the first meeting on Lorentz and CPT Symmetry, held in Bloomington in 1998, the number of experimental results measuring SME coefficients has snowballed. The full listing spans the sectors of physics and is growing yearly [10]. Details of individual presentations can be found in the conference proceedings, volume V in the series [11].

The SME is a realistic effective field theory in which the coefficients for Lorentz breaking could arise from spontaneous symmetry breaking in a fundamental theory such as string theory [12]. It exploits the fact that the effects of such symmetry violations could be detected at attainable energies in the context of effective field theory [13]. In the first CPT '10 talk, distinguished physicist James Bjorken, of the SLAC National Accelerator Laboratory, discussed these and other ideas surrounding spontaneously-broken symmetries. He provided a historical perspective on this field and discussed contributions made for example by Nobel laureate Yoichiro Nambu, who addressed the 2001 and 2004 meetings [14]. This set the stage for a productive meeting, running over a period of five days.

## 2. Antihydrogen

The production of antihydrogen in sufficient quantities for experimental studies holds the potential for new tests of Lorentz symmetry. Four groups at the European Organization for Nuclear Research, CERN, are currently working on aspects of the production and study of antihydrogen. They are the AEGIS (“Antimatter Experiment: Gravity, Interferometry, Spectroscopy”), ALPHA (“Antihydrogen Laser Physics Apparatus”), ASACUSA (“Atomic Spectroscopy and Collisions using Slow

Antiprotons”), and ATRAP (“Antihydrogen Trap”) collaborations, all of which were represented at CPT ’10.

The AEGIS group is aiming to measure the gravitational acceleration of antihydrogen, which would introduce experimental results into a subject of much theoretical interest [15]. In the initial phase, the goal is to measure the acceleration at the level of  $10^{-2}$  by detecting the free fall of a beam of antihydrogen passed through a Moiré interferometer [16]. The ALPHA collaboration aims to perform precision tests of CPT symmetry by comparing the spectra of antihydrogen and hydrogen. The group reported progress in the area of evaporative cooling of antiprotons, creation of trap conditions in which antihydrogen trapping is realistic, and the establishment of event selection criteria [17]. Soon after the meeting, the ALPHA collaboration reported success in trapping antihydrogen atoms in their apparatus [3]. The ASACUSA collaboration has had success with spectroscopic studies of antiprotonic helium. Recent results include an improved measurement of the spin magnetic moment of the antiproton [18]. The group has made progress towards the production of a spin-polarized antihydrogen beam, which they hope to use for spectroscopic measurements of the ground-state hyperfine transitions in antihydrogen atoms [19]. Such measurements have the potential to provide clean tests of the CPT symmetry [20]. The ATRAP group has had success trapping and probing the constituents of antihydrogen. It was first to demonstrate that antihydrogen could be produced within a nested Penning and Ioffe-Pritchard trap configuration [21].

### 3. Spectroscopy of atoms

The exceptional spectroscopic precisions possible with comagnetometers make them excellent systems for testing Lorentz symmetry. In these fast-developing experimental systems, the spin precession rates of several species of atoms can be compared with exquisite precision. The information can be used to place limits on anomalous couplings to Lorentz-breaking background fields. There are many different background fields, each coupling to different types of particles. For example, the  $b$ -type background fields are relevant for testing anomalous spin couplings in fermions, and there are different  $b$  coefficients for protons, neutrons, and electrons. Recently, a group at Princeton placed constraints at the level of  $10^{-33}$  GeV on the equatorial components of the  $b$ -type coefficients in the neutron sector, a 30-fold improvement on the previous mark [2]. These results were achieved with a new apparatus, CPT-II, that improved on several aspects of the earlier CPT-I device. The system, a K-He comagnetometer, is mounted on a rotary platform which allows for frequent reversals of its orientation. The main systematic is a coupling between the Earth’s rotation and the gravitational field, and the team has discussed the interesting possibility of removing this limitation by running

the experiment near the South pole.

A comagnetometer based on helium and xenon atoms at the Harvard-Smithsonian Center for Astrophysics generated a number of the first limits on neutron coefficients for Lorentz violation [22, 23]. More recently, a helium-xenon comagnetometer at the Physikalisch-Technische Bundesanstalt (PTB), the national metrology institute in Berlin, has been commissioned and is generating competitive limits [24].

Clock-comparison experiments are sensitive to a variety of SME coefficients [25] and have led to sharp constraints on Lorentz violation using cesium fountain clocks [26] in addition to the devices mentioned above. Recent work shows that the reach of these experiments can be extended by taking into account various effects, such as the binding energies of nucleons, the velocity of the Earth at different points on its orbit, and the axial precession of the Earth [27].

A clock-comparison experiment run at the Laue-Langevin Institute in Grenoble has the distinction of being the first Lorentz test based on an experiment with free neutrons. It compared the spin precession frequencies of ultra-cold neutrons and mercury atoms, placing limits on a combination of SME coefficients [28].

#### 4. Cavity Oscillators and the minimal SME

Experiments with high-precision optical and microwave oscillators have shown steady increases in their ability to probe Lorentz symmetry for a number of years. These have mainly focused on the minimal SME [9, 29], which is made up of dimension 3 and 4 operators that break Lorentz symmetry. In the photon sector, all the dimension-3 operators, and 10 of the 19 dimension-4 operators control birefringence and are tightly constrained by exploiting the long baselines of astrophysical observations. The remaining 9 nonbirefringent operators in the minimal SME have been the focus of a number of rapidly-evolving laboratory tests involving various precision cavity oscillators. There are at present more than 130 limits on individual SME coefficients in the minimal photon sector [10], resulting from work done since 2003.

Presentations by several of the experimental groups working in this area were given at CPT '10. An apparatus at the Humboldt University in Berlin has two crossed cavity oscillators and a monolithic optical sapphire resonator. The design builds on earlier oscillators that have generated some of the highest resolution tests of Lorentz symmetry in the photon sector [5]. Recently, results obtained at the University of Western Australia, using an oscillator that operates in the ‘whispering gallery’ mode, were used to place limits on all 9 nonbirefringent coefficients in the minimal photon sector. The group has introduced numerous innovations [30], and their latest results include an improved limit on one of the isotropic parameters of the SME [31]. The

Australian group is joining forces with the Humboldt University experimentalists by bringing their apparatus to Germany. This will further increase the ability of these systems to generate refined tests of Lorentz symmetry. Another German group, based in Düsseldorf, has pushed the precision boundary by placing limits on SME coefficients with a cavity experiment investigating the isotropy of the speed of light [4].

Many other physical systems in the photon sector have played a part in studies of Lorentz violation, including, for example, Čerenkov radiation [32], nonlinear studies [33], the Chern-Simons term [34], and statics [35].

## 5. Nonminimal coefficients in the electromagnetic sector

Several higher-order Lorentz-breaking effects were presented at the CPT '10 meeting, based on recent work that has completed the challenging task of producing a systematic order-by-order account of all the terms [36]. The complete characterization of these coefficients for Lorentz violation involves a decomposition in terms of spin-weighted spherical harmonics. The formalism is adapted to provide information about which coefficients control birefringence, dispersion, and anisotropy under vacuum or other boundary conditions, thereby helping to make the distinction between astrophysical and laboratory tests. At the CPT '10 meeting, presentations discussing experimental limits on nonminimal coefficients included ones made by representatives for astrophysical tests, such as ones with the Fermi telescope [37], and laboratory tests, as with cavity oscillators [38]. As of January 2011, there exist limits on higher-order photon-sector operators of dimensions 5 through 9, based on astrophysical birefringence, cosmic-microwave-background polarization, and astrophysical dispersion [10].

## 6. Gravity-sector studies and tests

The framework for Lorentz violation in curved spacetime was established several years ago [39]. Details of the theory and experimental signals arising from couplings of the background fields to the pure-gravity sector have been investigated [40]. They have led to results on SME coefficients controlling couplings in the pure-gravity sector, based on lunar-laser-ranging data [41] and atom interferometer experiments [42, 43].

Recent work on the couplings of the background fields to the matter sector [44] was presented at CPT '10. The results indicate a broad range of possibilities for experimental investigations, many of which involve atomic, molecular, and optical physics. Laboratory tests studied include ones with free-fall and force-comparison gravimeters, and others with free-fall and force-comparison weak-equivalence-principle devices. Many of the tests are limited by the time of free fall of test masses. The

proposed Sounding-Rocket Principle Of Equivalence Measurement, SR-POEM, [45] can increase this time up to several hundred seconds. Weak equivalence principle tests can also be conducted in space, where test bodies can be compared after almost unlimited periods of free fall. Several satellite missions have the potential to perform tests, and include for example the Satellite Test of the Equivalence Principle, STEP, which was represented, together with Gravity Probe-B, at the CPT '10 meeting [46]. Tests of a more exotic type might include charged-particle interferometry, comparisons of hydrogen and antihydrogen, and tests with second- and third-generation particles such as muonium. Solar-system tests are also of definite interest, and include lunar and satellite laser ranging, as well as perihelion precession of Mercury and the Earth.

Another category of tests would look for gravitational couplings with Lorentz violating background fields based on the Shapiro time delay, the gravitational Doppler shift, and the gravitational redshift. Recent work at the University of California, Berkeley, has focused on the relationship between different types of gravitational redshift experiments, and has tested the Einstein equivalence principle by placing limits at the level of parts in  $10^6$  on coefficients that control spin-independent couplings of SME fields with the matter sector [1].

A key result in the fundamental theory of Lorentz violation is the incompatibility of explicit Lorentz symmetry breaking with generic Riemann-Cartan geometries, a limitation that is evaded by spontaneous Lorentz breaking [39]. Consequently, a number of studies have been made of theories involving tensor fields with potentials that trigger spontaneously-broken Lorentz symmetry. These fields include the bumblebee  $B_\mu$  [39, 47], the symmetric-index cardinal  $C^{\mu\nu}$  [48], and an antisymmetric two-tensor  $B_{\mu\nu}$  [49]. These investigations have shown intriguing connections with Einstein-Maxwell theory, and general relativity, and have led to a rich body of results relating to massless and massive propagating modes.

Experiments from the realm of atomic, molecular, and optical physics have exploited the relationship between Lorentz-breaking fields and spacetime torsion [50] to place limits on the latter [51]. Several talks at CPT '10 addressed aspects of torsion, including its relation to effective field theory [52], and to rotating Kerr black holes [53]. Related work has investigated the classical lagrangians with Lorentz violation [54] that follow from SME-based dispersion relations [55], and the associated Riemann-Finsler geometries [56, 57, 58]. Torsion has also been studied as a background [59], and in the context of Lorentz violation and galactic dynamos [60].

## 7. Accelerator-based AMO experiments

A Compton-scattering experiment at the GReNOble Anneau Accélérateur Laser (GRAAL) beamline of the European Synchrotron Radiation Facility (ESRF) in Grenoble has recently led to a sharp test of Lorentz symmetry. Calculations show that when a photon is scattered from a free electron the maximal energy of the backscattered photon, the Compton-edge energy, is sensitive to sidereal Lorentz-breaking effects. Since the sensitivity goes like  $\gamma^2$ , the ultrarelativistic electrons at the ESRF, with  $\gamma = 11800$ , are ideally suited to a Lorentz test. The result [61] is an order of magnitude improvement on a combination of photon and electron coefficients in the SME.

Ives-Stilwell experiments, which measure Doppler shifts of spectral lines, offer another avenue for tests of Lorentz symmetry in the matter sector. Currently, measurements of optical transitions of lithium ions in a  $\beta = 0.34$  beam at the Experimental Storage Ring (ESR) of the GSI Helmholtz Center for Heavy Ion Research in Darmstadt are under way. It was reported at CPT '10 that the sensitivity achieved is on a par with an earlier experiment at the heavy-ion Test Storage Ring (TSR) at the Max Planck Institute for Nuclear Physics in Heidelberg, and that a further order of magnitude improvement is expected. Bounds on combinations of matter-sector coefficients for Lorentz violation were presented [62].

The DAΦNE collider at Frascati has the potential to provide experimental results on SME coefficients for the neutral kaons [63]. Details of the types of signals and analyses from the Frascati KLOE and KLOE-2 experiments were presented at CPT '10 [64].

## 8. Other sectors

The SME has had remarkable success in resolving the anomalies observed in neutrino experiments in recent years. The usual three-neutrino Standard Model is not able to account for recent anomalies [65] seen in the Liquid Scintillator Neutrino Detector (LSND) signal, the Mini Booster Neutrino Experiment (MiniBooNE) low-energy excess, and the neutrino-antineutrino differences in the MiniBooNE and the Main Injector Neutrino Oscillation Search (MINOS) experiments. Several talks at CPT '10 addressed neutrino physics, and included a presentation of the basic theoretical framework for Lorentz- and CPT-violating effects in this sector. The theory demonstrates that differing limits are relevant for analyses of short- and long-baseline experiments [66]. Several models have been studied [67]. Preliminary experimental results from the neutrino sector presented at the meeting showed that SME coefficients for Lorentz violation can be fitted to experimental data from the LSND and MiniBooNE experiments [68]. More recently, a seven-parameter model, the ‘puma,’ has been built within this SME framework. It is the first model consistent with all compelling neutrino data and the

LSND, MiniBooNE, and MINOS anomalies [8].

Another anomalous result in the context of B-meson oscillations has been interpreted in terms of the SME, based on the findings [69] of the D0 collaboration at FermiLab. The resulting constraint [7] at the level of parts in  $10^{12}$  is the first sensitivity to CPT violation in the  $B_s^0$  system.

## 9. Conclusion

The energetic and innovative work put forth by the AMO community in pursuing the possibility of Lorentz violation in nature continues to lead to technological advances and the prospect of exciting results. The *Fifth Meeting on CPT and Lorentz Symmetry* provided a forum for the community to get updated on developments. This article emphasizes the AMO physics at the meeting, although many other topics, such as superfields [70], topological defects [71], quark condensation [72], linearized gravity [73], and coordinate invariance breaking [74] were also discussed. Experiments continue to allow ever deeper searches into the details of nature, while theoretical developments have provided additional untested regions of coefficient space. Areas of investigation that are likely to lead to experimental limits in the coming few years include coefficients controlling nonminimal couplings in the SME, and others controlling gravitational couplings. It is clear that tests of the fundamental symmetries of nature are profoundly interesting to a broad community of physicists, and one can hope that new territory will be revealed as this frontier is further explored.

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